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TRENDS IN EARTH-TO-ORBIT SPACE TRANSPORTATION SYSTEMS

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by

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IN GERMAN

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*The opinions expressed in this paper are those of the author and not necessarily those of the National Aeronautics and Space Administration.

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ZUSAMMENFASSUNG

Die Entwicklungen der letzten fünf Jahre auf dem Gebiet der Raum-Transportsysteme zwischen Erde und Erd-Kreisbahn werden kritisch untersucht. Darauf folgt eine allgemeine Diskussion, warum eine weitere erhebliche Verbesserung in der Technik Lasten und Personen zur Erd-Kreisbahn zu befördern, zu erwarten ist. Verschiedene wesentliche charakteristische Systemgrössen werden für einen Zeitraum von Zwei Jahrzehnten extrapoliert, wobei ein hypothetisches Model der Lastraketenentwicklung und des Verkehrsbedarfes der Rechnung zugrunde gelegt wird. Es wird ferner gezeigt, dass die "spezifischen direkten Betriebskosten" für den Lastentransport zur Erd-Kreisbahn im Laufe einer Generation um vier Grössenordnungen verbessert werden dürften. Ferner ist zu erwarten, dass die Verkehrsleistung (ausgedrückt in Tonnen Nutzlast in der Erd-Kreisbahn pro Jahr) in zwanzig Jahren um fünf Grössenordnungen ansteigen dürften.. Es wird gefolgert, dass dieses Anwachsen der Verkehrsleistung es möglich machen sollte, gegen Ende der siebziger Jahre eine grössere Zahl von Raumfahrt-Projekten, einschliesslich Aussenstationen, Mondstation(en) und Planetare Expeditionen gleichzeitig durchzuführen.

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ABSTRACT

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The accomplishments of space flight in the past five years are critically reviewed and initial trends are established for the efficiency of Earth-to-orbit space transportation systems. A general examination of launch vehicle development trends follows, indicating further reduction of space transportation cost. The trends which can be expected for characteristic system parameters of Earth-to-orbit space transportation systems are then projected on the basis of a hypothetical launch rate model. It is shown that the "specific direct operating cost" for cargo transportation to Earth orbit should improve by four orders of magnitude in one generation (25 years) and that our capabilities for accomplishing space missions should increase by five orders of magnitude over 20 years. It is concluded that the space transportation capacity for multiple orbital, lunar, and planetary programs should become available in the late 1970's.

I. INTRODUCTION

It is always interesting to take a broad look at the developments of the past and project these into the future, in spite of the great risk that these projections may be wrong. These projections, however, are subject to an iteration process, and when one forecasts the future often enough, the probability that one of these predictions may be right increases. Thus, this is just one of the many projections already made and probably more will follow in the future.

This paper is limited to a review of the developments of space transportation systems for Earth-to-orbit missions, which is only one specific region of activity where space transportation systems will be employed. No attempt will be made to justify the reasons why we should have space transportation systems at all, or why we should have a specific number of systems. It is simply assumed that we will accomplish as much space flight as we can afford, or more accurately, as we possibly "could" afford.

Five years of actual experience in Earth orbital transportation already gives us some very interesting trends when analyzed systematically. There is a wealth of information on the subject available in open literature. Some estimates as to the actual weight of the Russian COSMOS series is required to complete the picture. This analysis of the past is presented in Section II of this paper.

A general discussion of "why" the efficiency of space transportation systems should improve in the forthcoming decades is contained in Section III of this discussion. This, also, is based on data published in numerous papers and news releases. No effort was made to derive very accurate figures, as the intention of this paper is to show general trends only.

Finally, Section IV describes a hypothetical model of future activities in the area of Earth-to-orbit transportation which permits the development of some interesting trends over the period of one complete generation (25 years). Since

Earth-to-orbit transportation is an essential element of all space transportation systems, these trends can also be considered typical for lunar and planetary space transportation.

II. TRENDS OVER THE PAST FIVE YEARS

Some of the most important system parameters of Earth-to-orbit transportation are: (1) Single flight payload capability, (2) number of launch attempts per year, (3) cumulative number of space launches, (4) annual weight delivered, (5) cumulative equivalent payload weight delivered, (6) achieved mission reliability, (7) total direct operating cost per year, and (8) specific direct operating cost to Earth orbit. All these trends are plotted versus time in Figures 1 through 8. Most of the information shown is selfexplanatory, but some pertinent comments can be made as follows:

Single flight orbital payload capability. The data shown in Figure 1 are nominal payload capabilities for a low altitude orbit of about 325 km. It is evident that the USSR has been leading the USA in this aspect ever since Sputnik 1. This year promises to be an interesting one, as both countries are expected to make a big jump. One of the early SATURN I two-stage launch vehicles may orbit a payload in the 10-ton class late this year. Also, the author would not be a bit surprised if the USSR would launch a payload in the 40- to 50-ton class before this year is over. The next step increase will be provided by the SATURN V in about 1967, when a 100-ton capability will be reached by the USA. Many people hope that at least by that time the USSR single flight capabilities will have been equalled or exceeded.

The number of space launch attempts versus time (Figure 2) shows a different picture. The USA is the undisputed leader, even if one includes a few more failures which might have occurred and not been counted on the side of the USSR. The annual firing rate has increased sharply and very few people, not even the optimists, would have predicted five years ago that an average of

one launch per week would have been accomplished as early as calendar year 1962. The same trend is amplified if the cumulative number of all space launches is plotted vs time (Figure 3).

If one assumes, now, that all flights which have reached at least orbital speed, regardless of destination, would have carried satellites into a low altitude orbit, and all these weights were added up over each year, the trend shown in Figure 4 emerges. We are surprised to find that in 1962 the USA may have equalled the USSR in this performance parameter for the first time. A word of caution, however, is in order, as neither the weights of the USAF satellites nor those of the COSMOS series have been announced; therefore, nominal average figures have been assumed; e.g., 1.5 tons for a satellite for the COSMOS series. Thus, one gets the impression that the USA is rapidly narrowing the gap as far as total payload weight orbited is concerned, a trend which is also apparent from Figure 5. If this trend continues, the USA will, in a couple of years, have orbited more payload weight than the USSR. If this really materializes, it will be comforting to a great number of people; however, this is but one yardstick of the space race.

Taking a look at the overall reliability (number of successful launches divided by the number of total attempts) shows clearly that great progress has been made (Figure 6). This curve is based on USA launches only. It is surprising to note that a figure of better than 85 percent reliability has been achieved in 1962. This also shows that the pessimists were wrong.

Finally, we know that certain costs are connected with the procurement of each launch vehicle, its propellants, and its launch operations. If one adds up all these costs (not including the development cost) for all vehicles launched successfully or unsuccessfully in any particular year, one obtains the trend shown in Figure 7. This information is needed to develop the "specific direct operating cost" as a function of time, as shown in Figure 8, which is the total

annual direct operating cost divided by the total equivalent orbital weight of all successful space launches made by the USA. By examining Figure 8, we can see that substantial progress has been made in the last five years, but the curve is leveling out at present because the launch vehicles used now (such as the THOR- and ATLAS-based orbital carrier vehicles) have achieved a high degree of maturity and we must wait for newer and bigger launch vehicles before we can expect a major reduction in the specific direct operating cost.

These have been the trends in the past; let us now take a look at the state of the art in general, before we attempt to project some specific system parameters into the future.

III. GENERAL TRENDS IN THE STATE OF THE ART OF LAUNCH VEHICLES

There are several reasons why we should expect greater efficiency in space transportation in the future. Some of the more important ones are the development of bigger launch vehicles, the use of high energy propellants in upper stages, the use of better and lighter materials, and last, but not least, the rapidly growing experience in the field in general.

A few diagrams may illustrate this trend. A very good yardstick for the efficiency of a launch vehicle is the "growth factor," which is the take-off weight of a launch vehicle divided by its payload weight. This factor, when plotted vs time or vs payload size, shows a clear trend of improvement (Figures 9 and 10). This is to be expected; however, of particular interest is the gradient of these trend curves and the change of these gradients. It appears that it will be increasingly more difficult, during the next decades, to improve this factor much in Earth-to-orbit missions, a fact which is not necessarily true for Earth-lunar and Earth-planetary systems where nuclear propulsion will play an important role.

Another interesting parameter to examine is the "specific launch cost" which is the cost per unit of launch weight. The dots shown on Figures 11 and 12

represent typical launch vehicles which have reached or are expected to reach operational status, defined as a successful orbital launch. Figure 11, a plot of this parameter vs time, shows a clear trend while Figure 12, plotted vs take-off weight, shows more scatter but still a recognizable trend.

The previous illustrations have not included the research and development cost which must be met before a launch vehicle becomes available for operational launches. One would expect that the experience gathered, as well as the improvements in technology, should show a trend. This indeed is true, as we can see from Figure 13 where the research and development cost is plotted vs the launch vehicle payload capability. If one considers that the Scout and Delta vehicles have profited from the Vanguard, and/or the military missile program, to a larger degree than other vehicles, one would conclude that they also follow the general trend. Thus we can expect to need less money in the future for developing a given payload capability provided experienced teams are utilized. It is indeed comforting to know that we are getting smarter in this business - this observation sometimes is not obvious.

We are now ready to expect dramatic changes in the trends for the future and, in spite of all the hazards involved, we will make a daring attempt to speculate what might happen in the next 20 years or so.

IV. PROJECTION OF GENERAL TRENDS IN THE EFFICIENCY OF EARTH-TO-ORBIT SPACE TRANSPORTATION SYSTEMS

A projection into the future cannot be made without assumptions. Fortunately, we have to make only a few, as the lead time for launch vehicle development is very long, and much has been written about future launch vehicles such as NOVA and reusable launch vehicles. Thus, we do not expect many surprises as far as technology is concerned. An assumption has to be made, however, with respect to the launch rate per year as this influences everything - total expenditures, reliability, and total weight delivered. The projection

made in Fugure 14 for launch rates is based on data published in congressional hearings and trade magazines, and extrapolated in such a fashion that they produce total direct operating cost which is within reason. These assumptions represent fairly sizable operations in Earth orbit, such as the supply of one or more space stations, a lunar base buildup, and some limited planetary expeditions. The resulting costs for the procurement of the required launch vehicles - some of them totally or partially reusable - for the propellants required, and for the launch operation have been summed up, and the annual rate is plotted in Figure 15. If one considers that the U. S. National Space Budget will probably reach the 7×10^9 dollar limit in fiscal year 1964, the one billion figure in 1968 and two billion in 1975 appear entirely realistic. The drop after 1977 is the result of a constant firing rate and further learning in cost and reliability. In general, these assumptions are quite arbitrary, but they are considered typical, and will be satisfactory for establishing trends for the efficiency of Earth-to-orbit space transportation systems in the time period considered.

The expected reliability trends in the next two decades are depicted in Figure 16. During the rest of this decade we will experience a reliability around 80 percent due to several new launch vehicles being introduced into the national launch vehicle program. As the reliability of these new vehicles improve, so will the annual average; we can expect a considerable improvement in the 1970's. This trend will be accelerated as fully and partially reusable launch vehicles are introduced.

Figure 17 is the result of the two previous charts, obtained by multiplying launch rates by payload capabilities and dividing this by the reliability. It shows the annual delivery rate, assuming that all launch vehicles would orbit satellite payloads in the low reference orbit. It might be interesting to compare this capability with the requirement for a small planetary expedition leaving Earth orbit - about 1,000 tons per ship for a fast Mars mission. We can see that, if

for no other reason than that of availability, we will have to wait at least until the early 1970's before such a mission can be attempted. If one wants to supply several space stations and a lunar station, and make a modest planetary expedition in one and the same year, one will probably need an annual firing rate of close to 10,000 tons. According to this extrapolation, we should be able to do all of these things in the late 1970's; that is, if we want to.

The resulting specific direct operating cost, for the program represented by our hypothetical model, is depicted in Figure 18, indicating an improvement of nearly two orders of magnitude in fifteen years, reaching a figure of 100,000 $/ton or 50 $/lb by 1980.

Let us now turn to the problem of passenger transport to Earth orbit. Figure 19 shows the price of a round-trip ticket,as it may develop, versus time, beginning with the early Mercury flights. With the introduction of the SATURN launch vehicle and the test flights of the three-man APOLLO capsule in 1965, we observe a considerable increase in this factor for two reasons: (1) The stay time in orbit increases, and (2) the three-man APOLLO capsule is a Moon ship and not built as an efficient passenger vehicle to orbit. Later versions of this launch vehicle will probably be capable of carrying 5 to 10 passengers with an increase in economy shown for the late 1960's. A further drop should be possible in the 1970's by introducing reusable launch vehicles which can also transport a larger number of people. We expect that a round trip will cost approximately 20,000 $/man in the late 1970's. If we take into consideration also the length of the trip and plot our trip cost in terms of $/day stay time in orbit, we do get a more gradual improvement with time as shown in Figure 20.

Finally, we can venture a guess on the number of manned round trips we should expect as space flight develops. This will depend mainly upon the mode of transportation which becomes available. If we can design launch vehicles in such a way that "ordinary people" (not just test pilots) can physically tolerate

a ride, more mission requirements will emerge. This should happen during the 1970's when winged, reusable launch vehicles might become available for passenger transport. A typical trend of annual trips vs time is shown in Figure 21, indicating 100 round trips by 1973, and possibly 500 by 1976. We ought to be prepared to provide the right means of transportation for such traffic, if and when it develops.

V. SUMMARY

It is apparent that we are moving fast in the development of the state of the art in space transportation systems. While air transportation needed two generations to improve the efficiency of passenger transport by three orders of magnitude, we expect to improve the economy of Earth-to-orbit cargo transportation by four orders of magnitude in one generation, as shown in Figure 22. This is possible only because technology, in general, is advancing at such a rapid rate. This improvement should lead us to a capability of handling space exploration and space travel at an annual rate as shown in Figure 23, where the national capability is given in terms of tons/year of equivalent Earth orbital weight vs time. While we orbited less than one ton in 1958, we will be able to orbit more than 10,000 tons a year in the late 1970's.

This leads us to the conclusion that we can afford several orbital, lunar, and planetary programs concurrently in the late 1970's and that the 1980's might find us approaching commercial space travel.

LITERATURE

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6. "Missile and Space Systems 1962," H. H. Koelle, Astronautics, November 1962, p.29 to 37

Figure 1

SINGLE FLIGHT ORBITAL PAYLOAD CAPABILITY

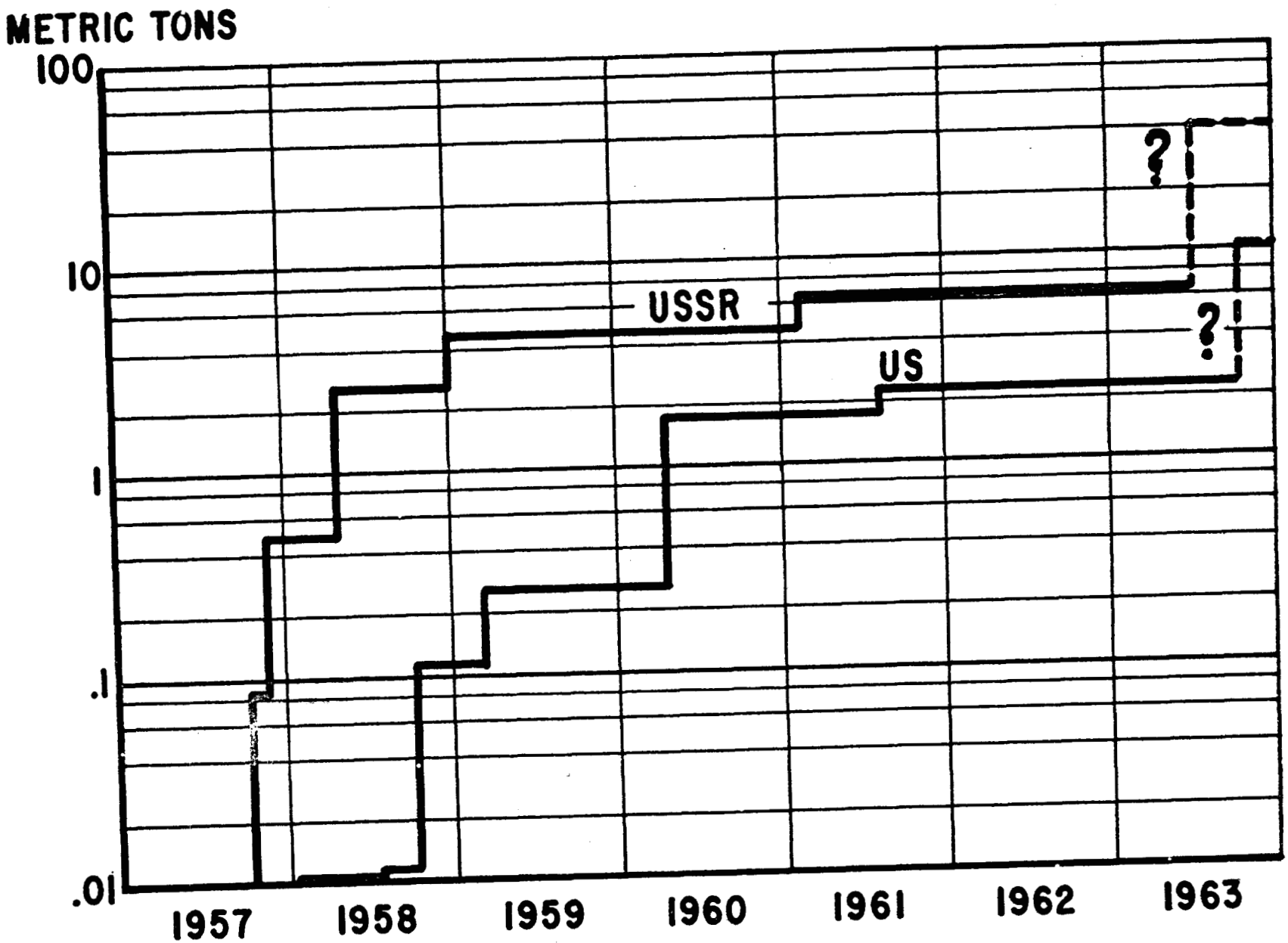

Figure 2

NUMBER OF SPACE LAUNCH ATTEMPTS PER YEAR

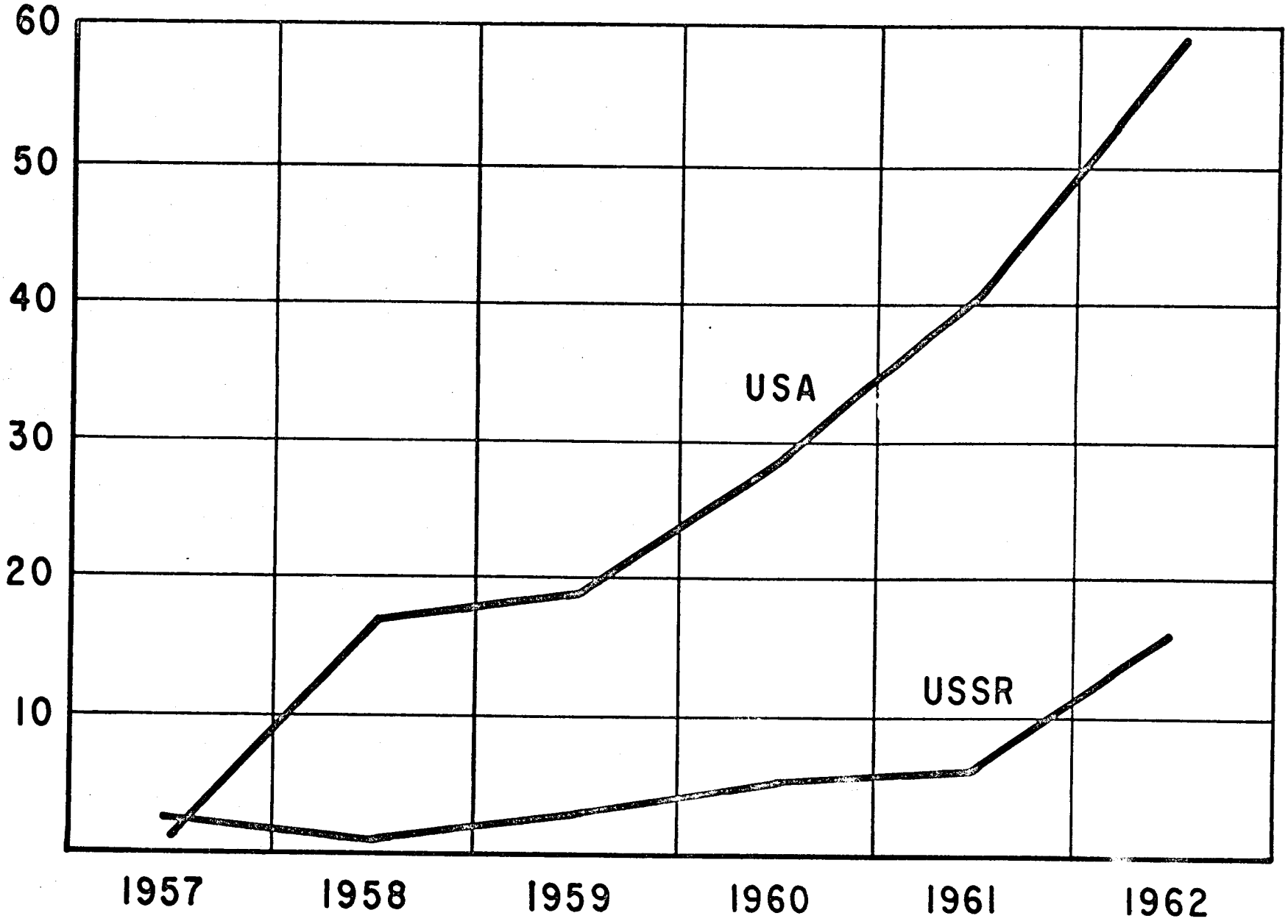

Figure 3

CUMULATIVE NUMBER OF SPACE LAUNCHES

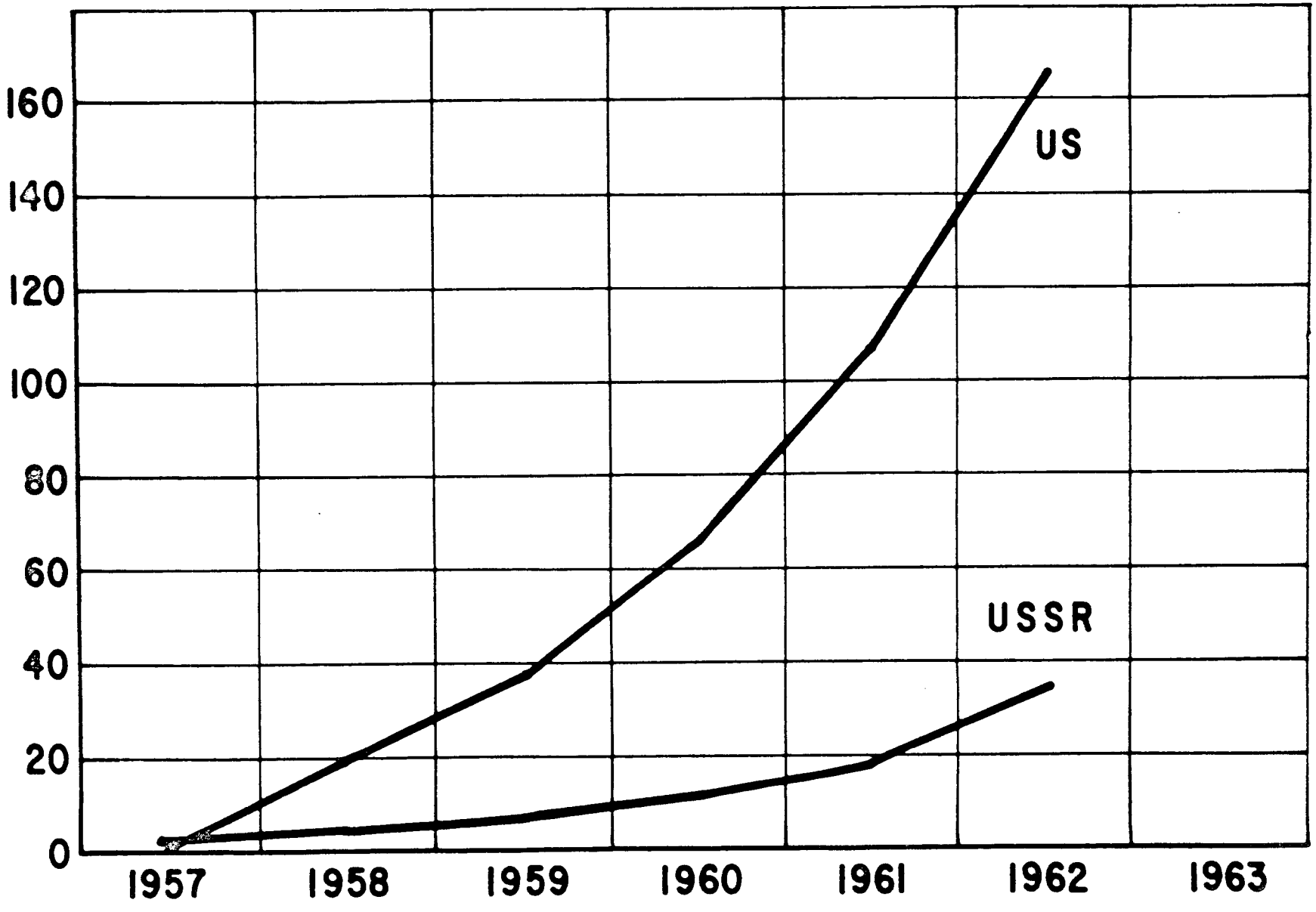

Figure 4

ANNUAL DELIVERY WEIGHT (EQUIVALENT PAYLOAD IN ORBIT)

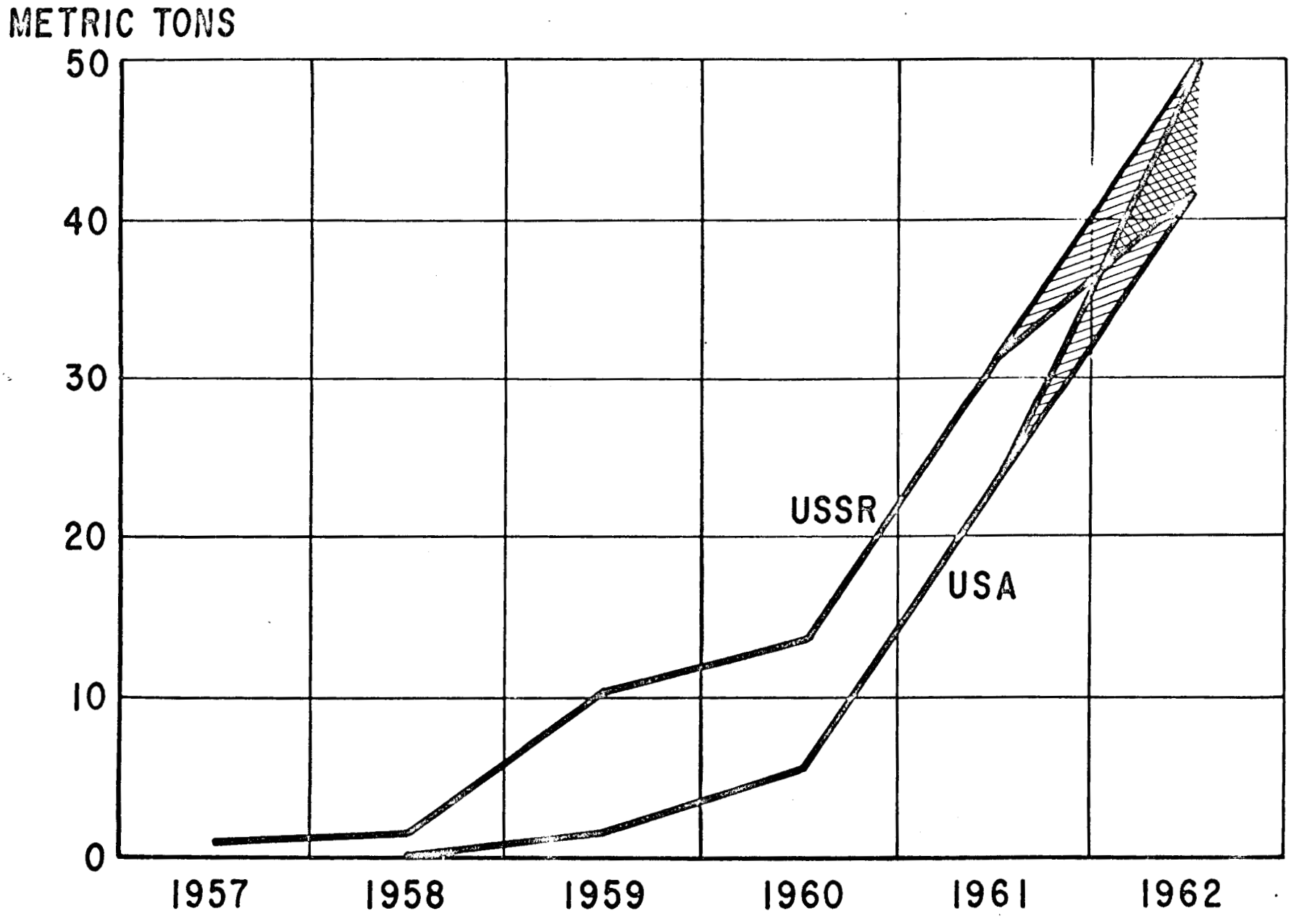

Figure 5

EQUIVALENT ORBITAL PAYLOAD WEIGHT
(CUMULATIVE)

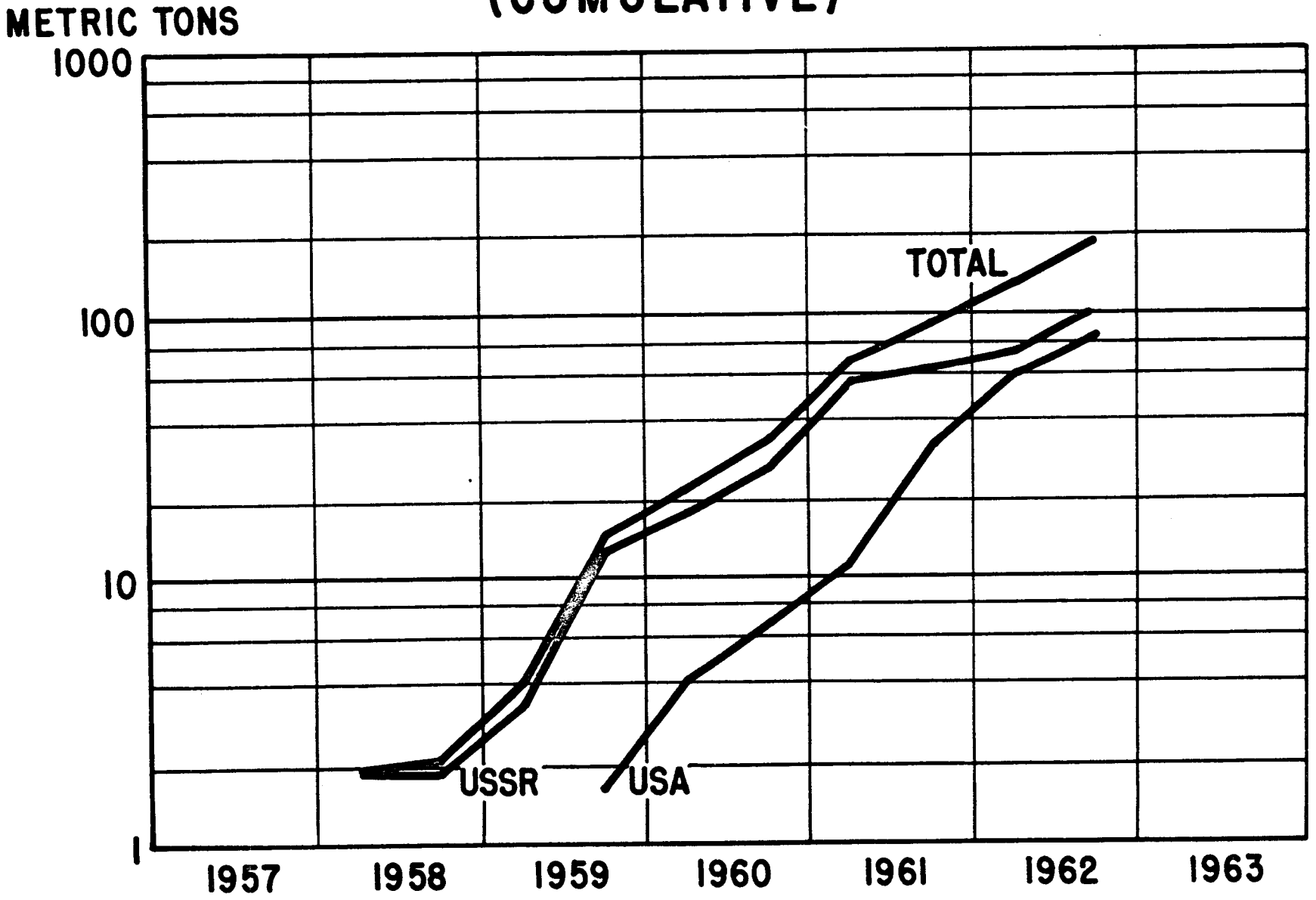

Figure 6

ACHIEVED SPECIFIC DIRECT OPERATING COST TO EARTH ORBIT

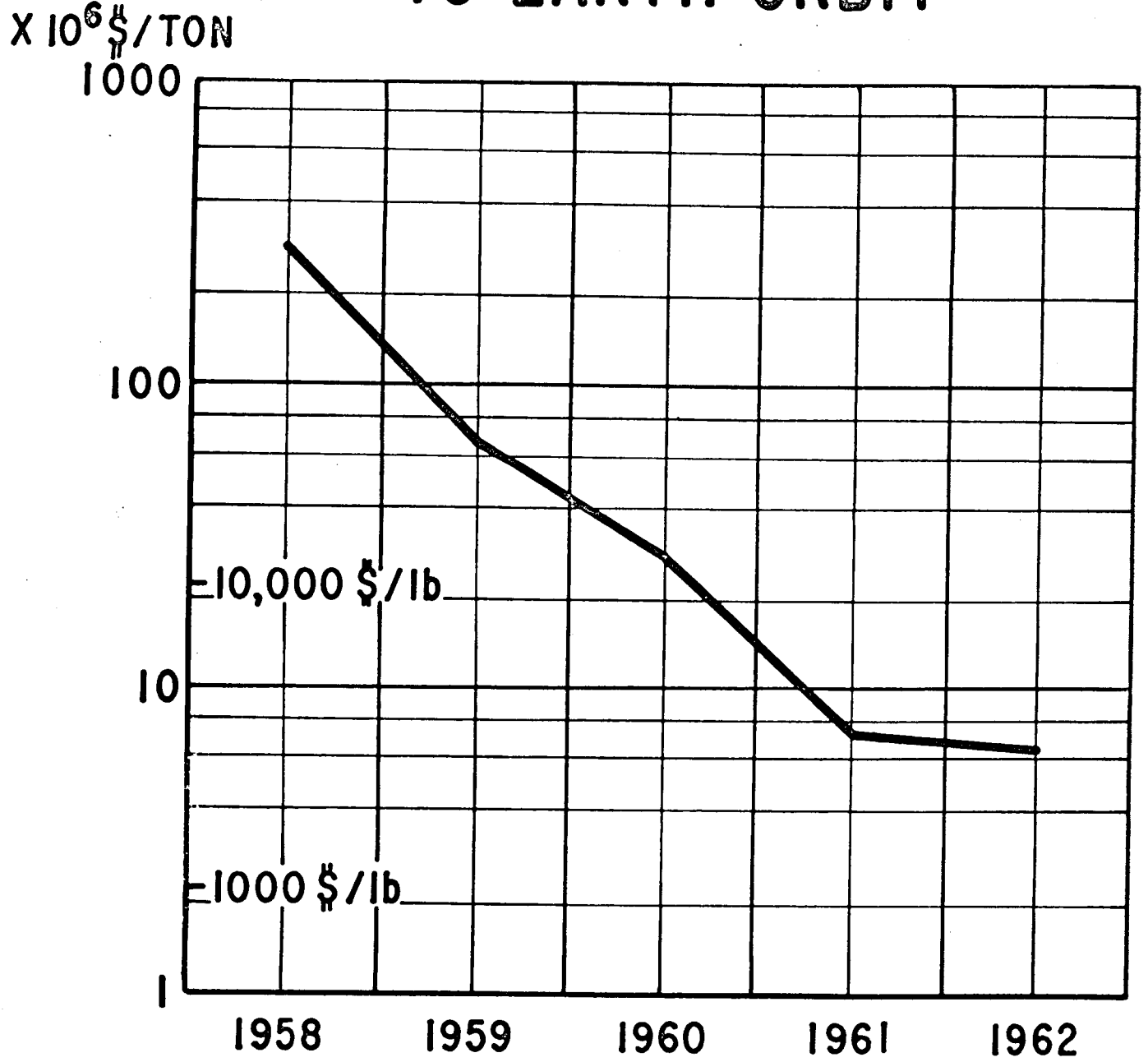

Figure 1

ACTUAL COST OF LAUNCH VEHICLE PROCUREMENT AND OPERATION PRO YEAR

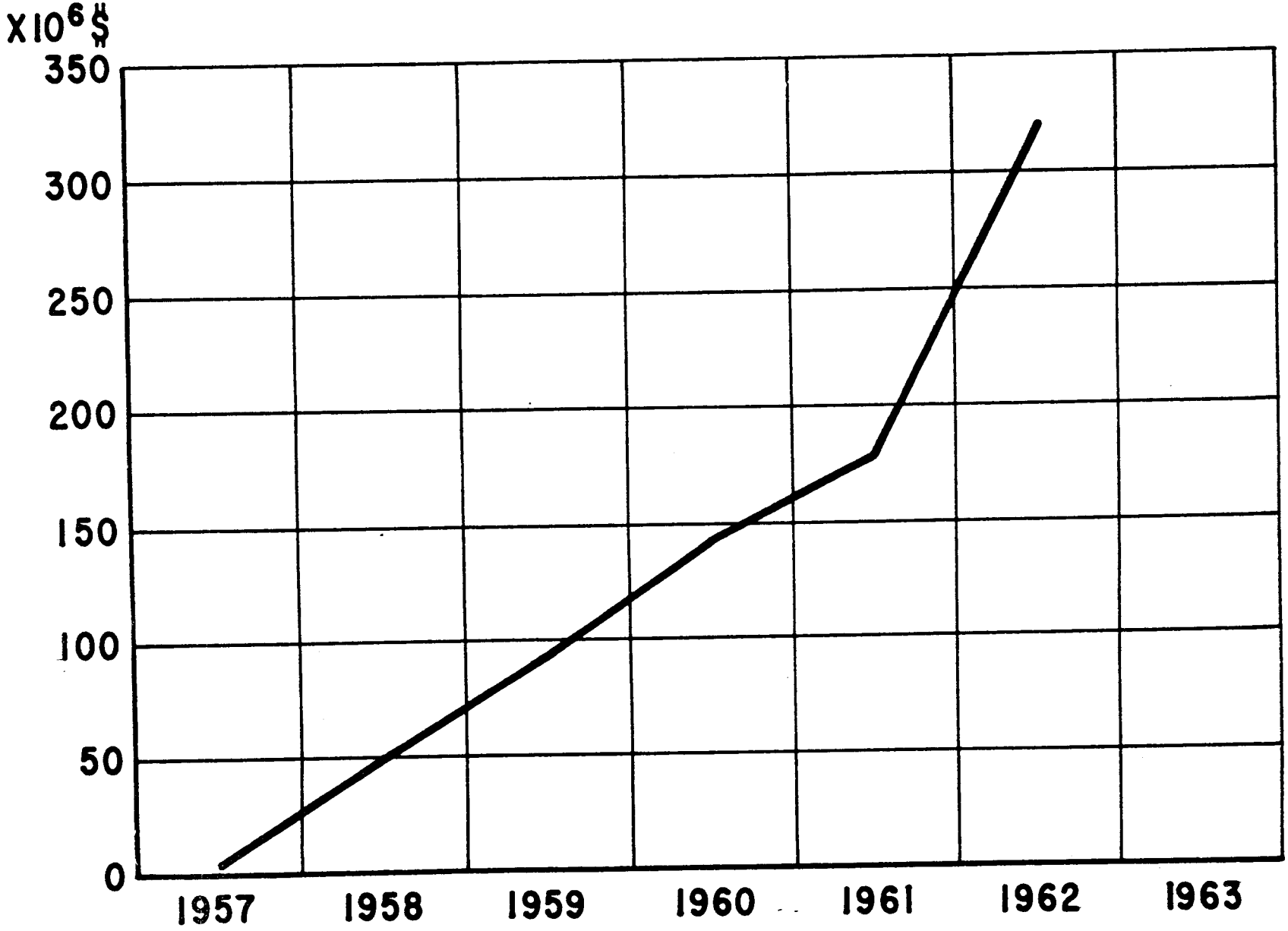

Figure 8

ACHIEVED SPECIFIC DIRECT OPERATING COST TO EARTH ORBIT

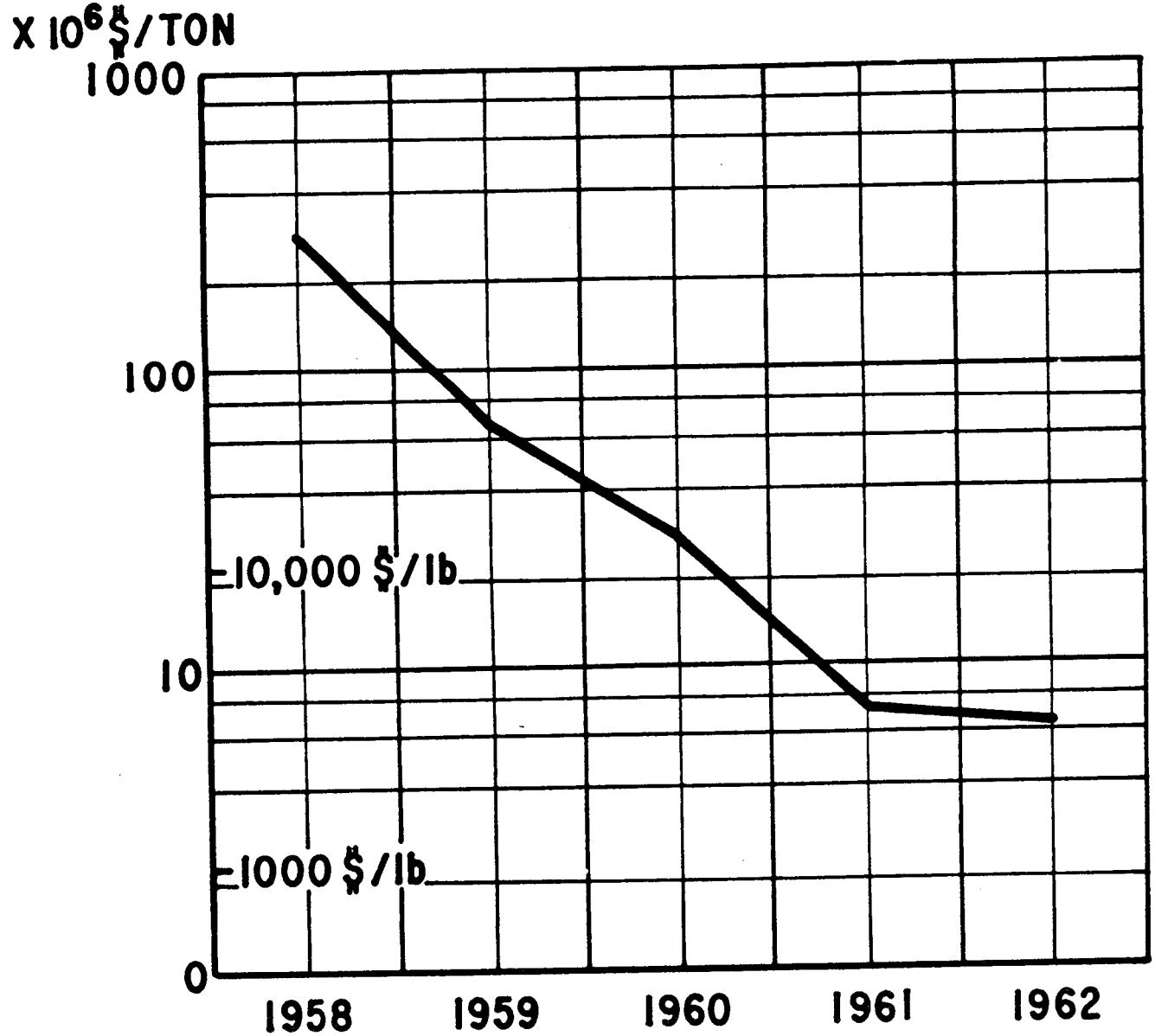

Figure 9

PROJECTED TREND OF LAUNCH VEHICLE GROWTH FACTOR

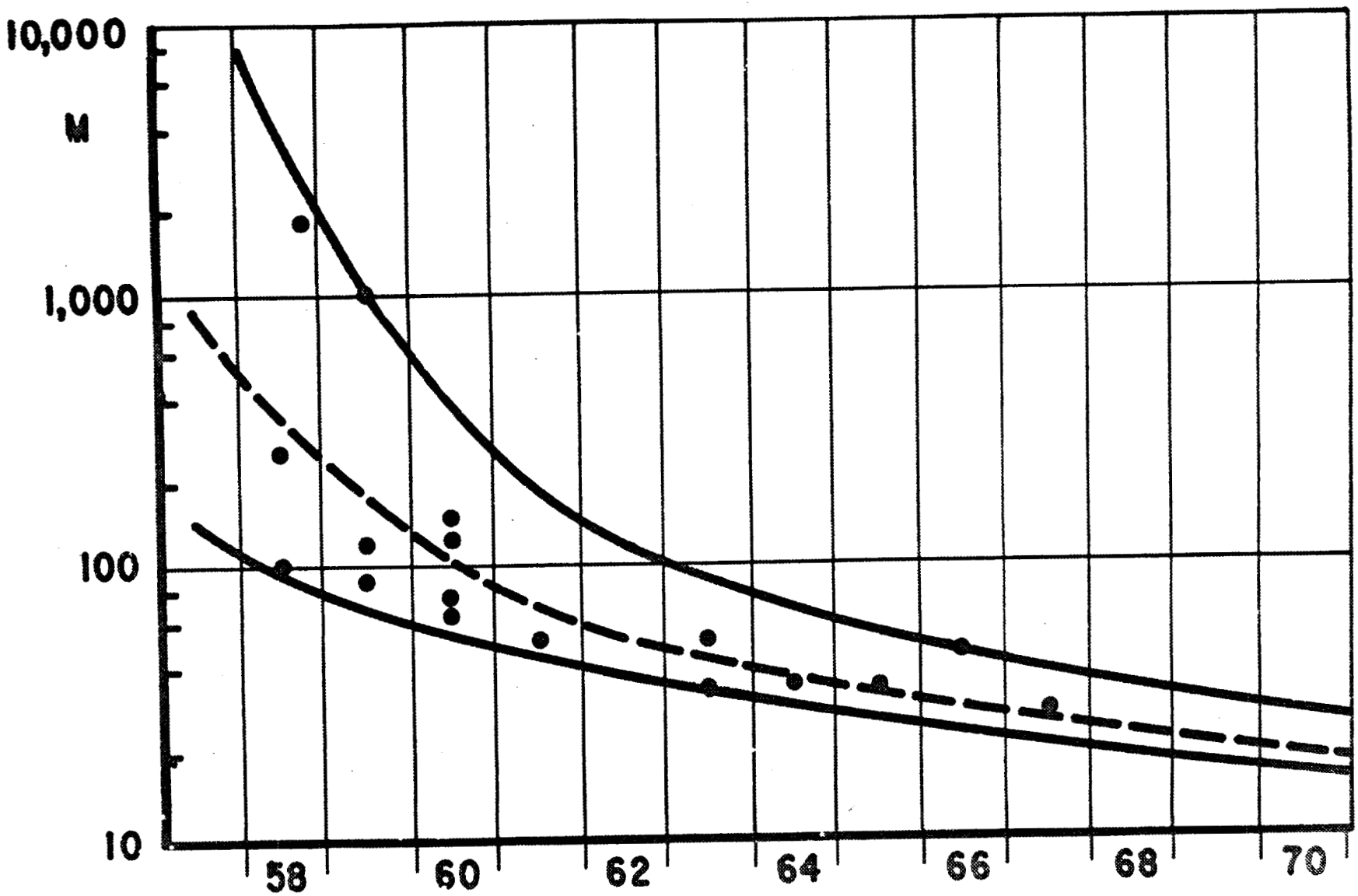

Figure 10

TREND OF LAUNCH VEHICLE GROWTH FACTOR

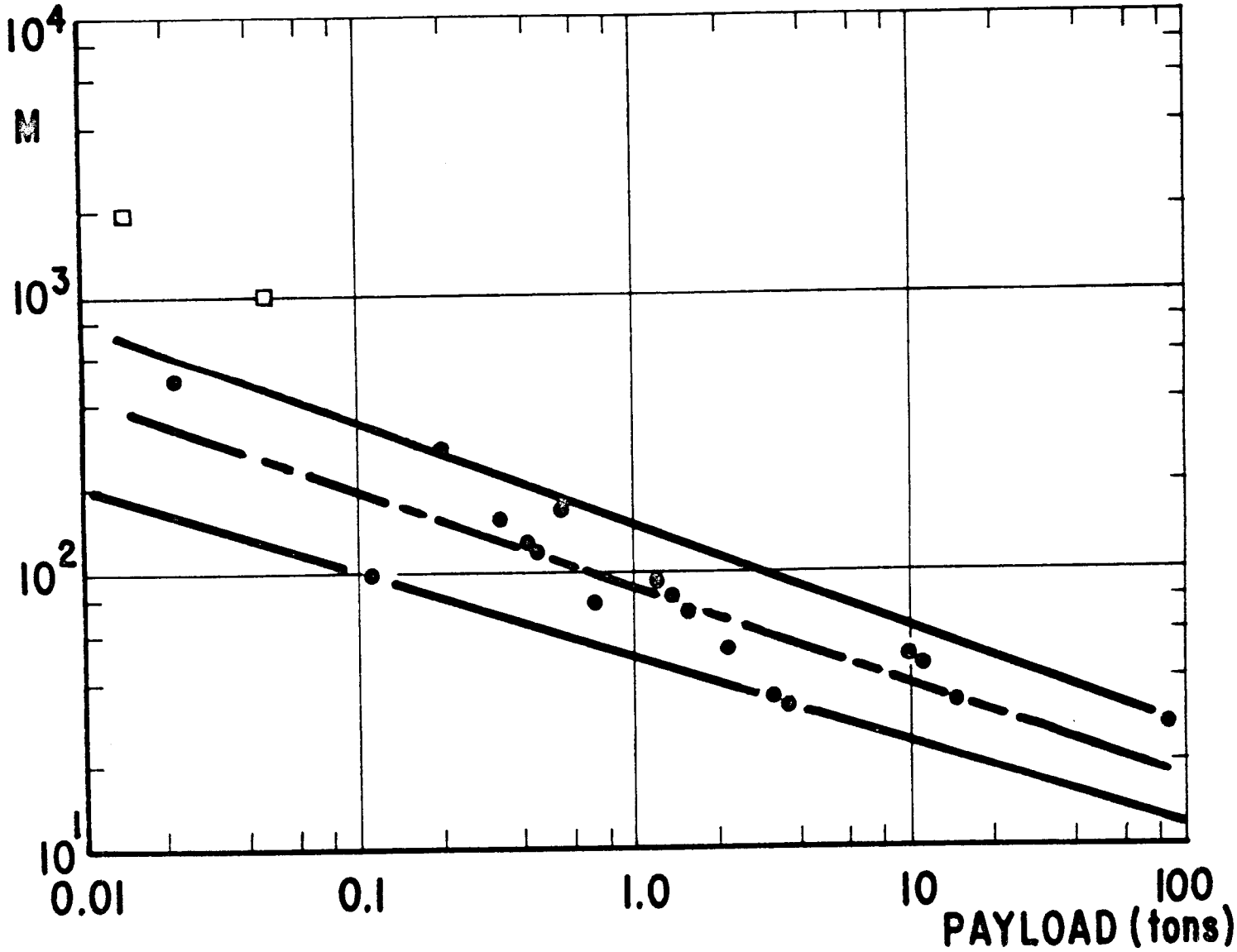

Figure 11

PROJECTED TREND OF SPECIFIC LAUNCH COST (DOC)

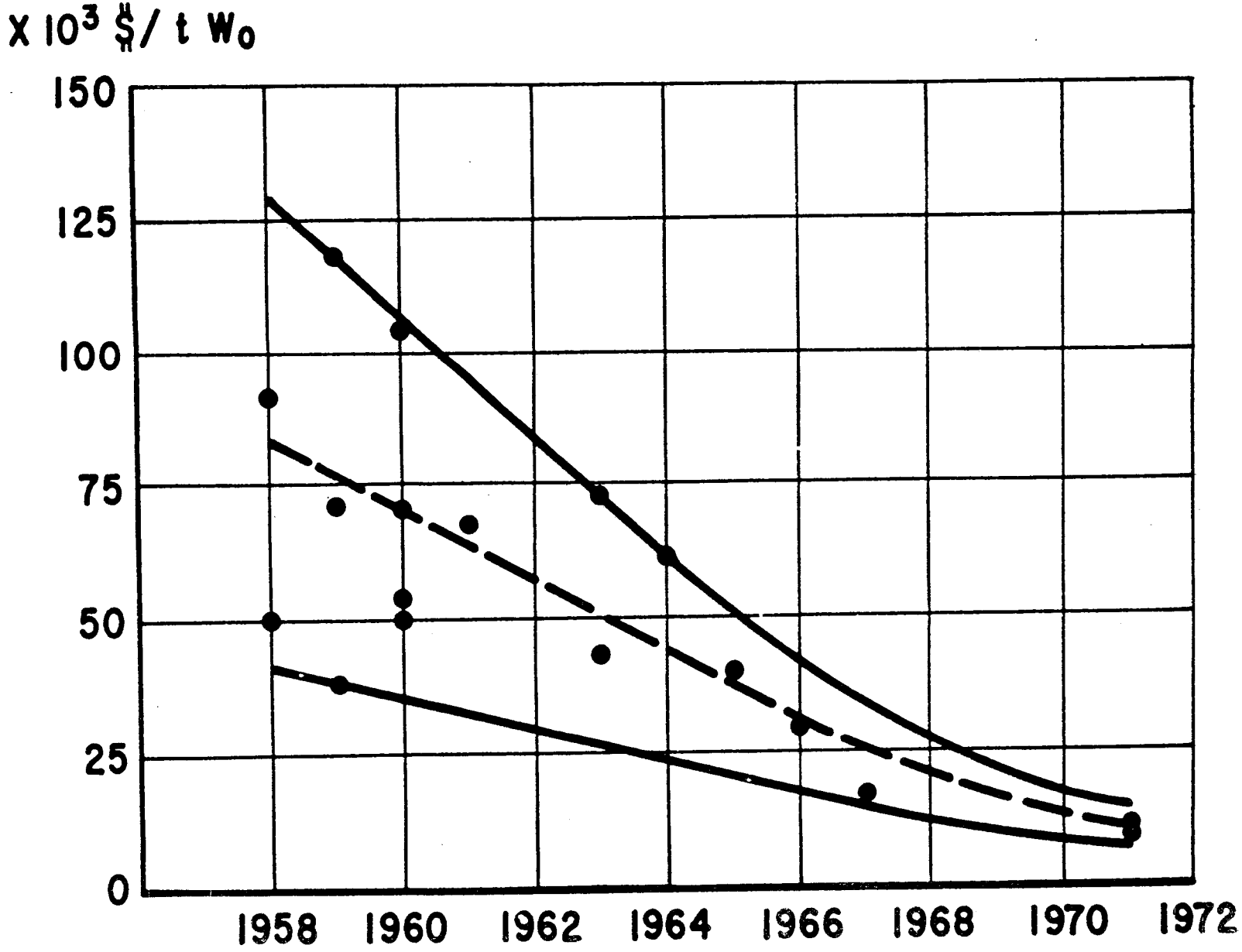

Figure 12

SPECIFIC LAUNCH COST (DOC)

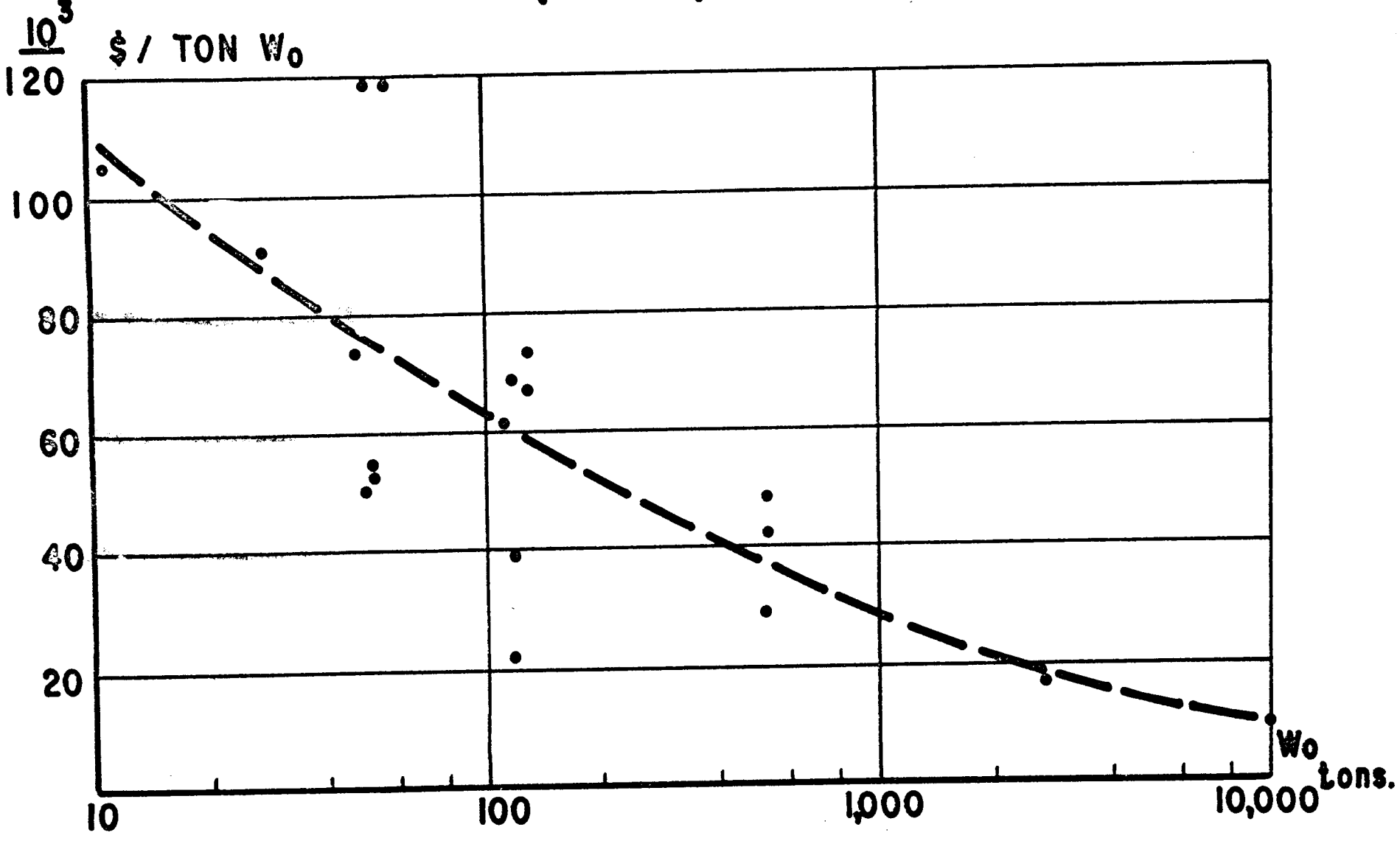

Figure 13

R & D COST

PER METRIC TON PAYLOAD CAPABILITY

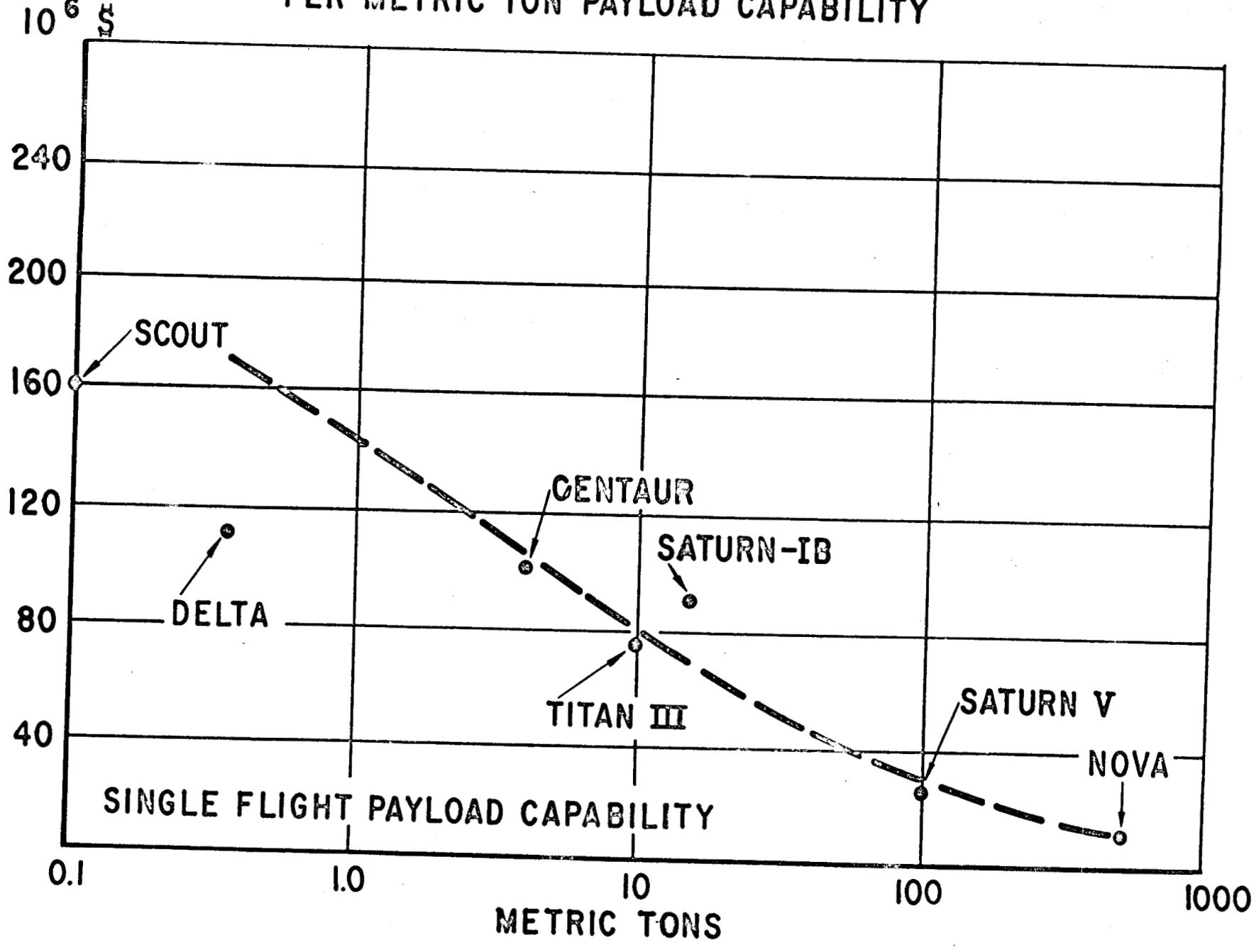

Figure 14

PROJECTED NUMBER OF FLIGHT ATTEMPTS (MODEL)

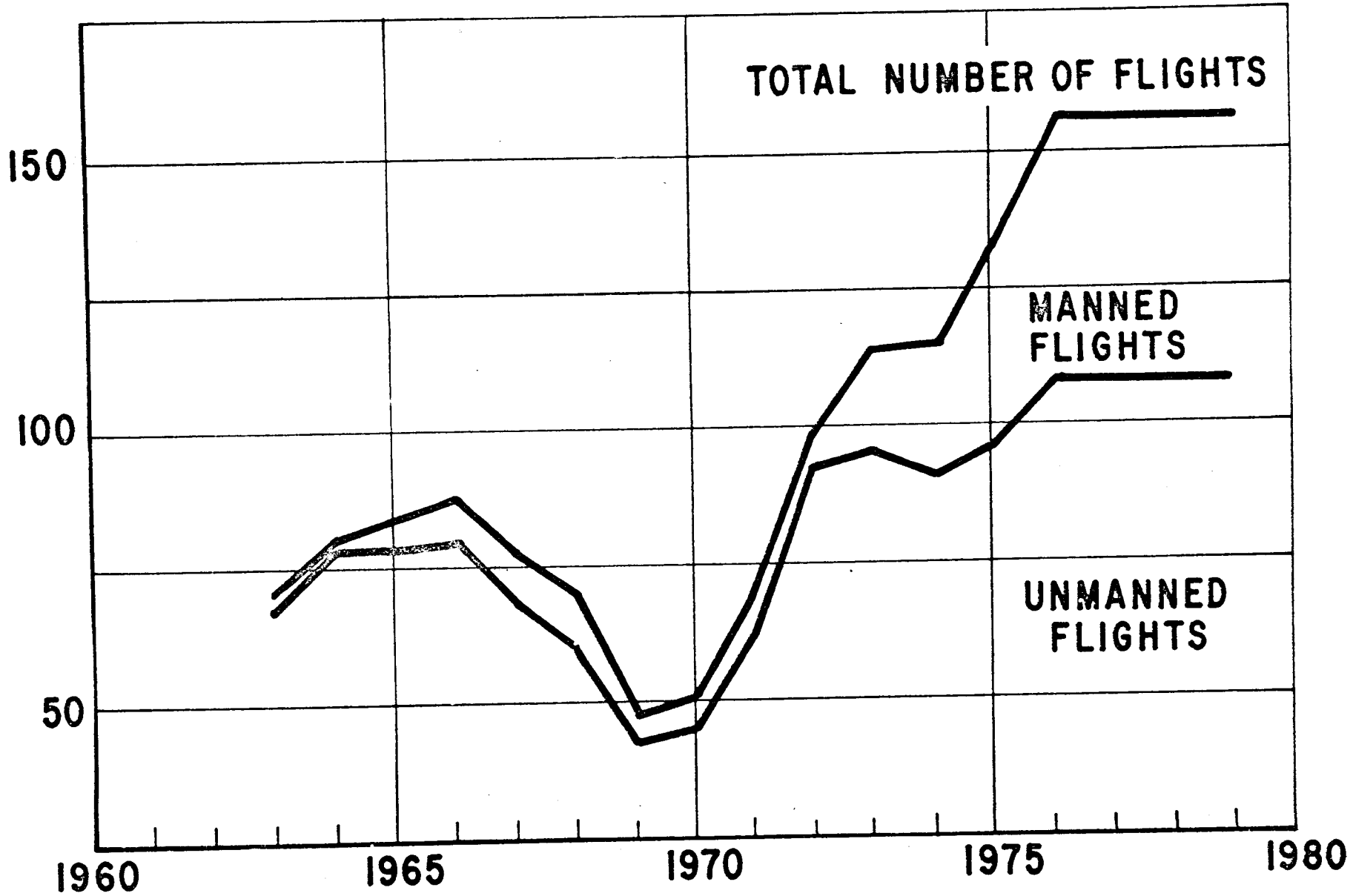

Figure 15

TOTAL DIRECT OPERATING COST FOR PROJECTED LAUNCH RATES

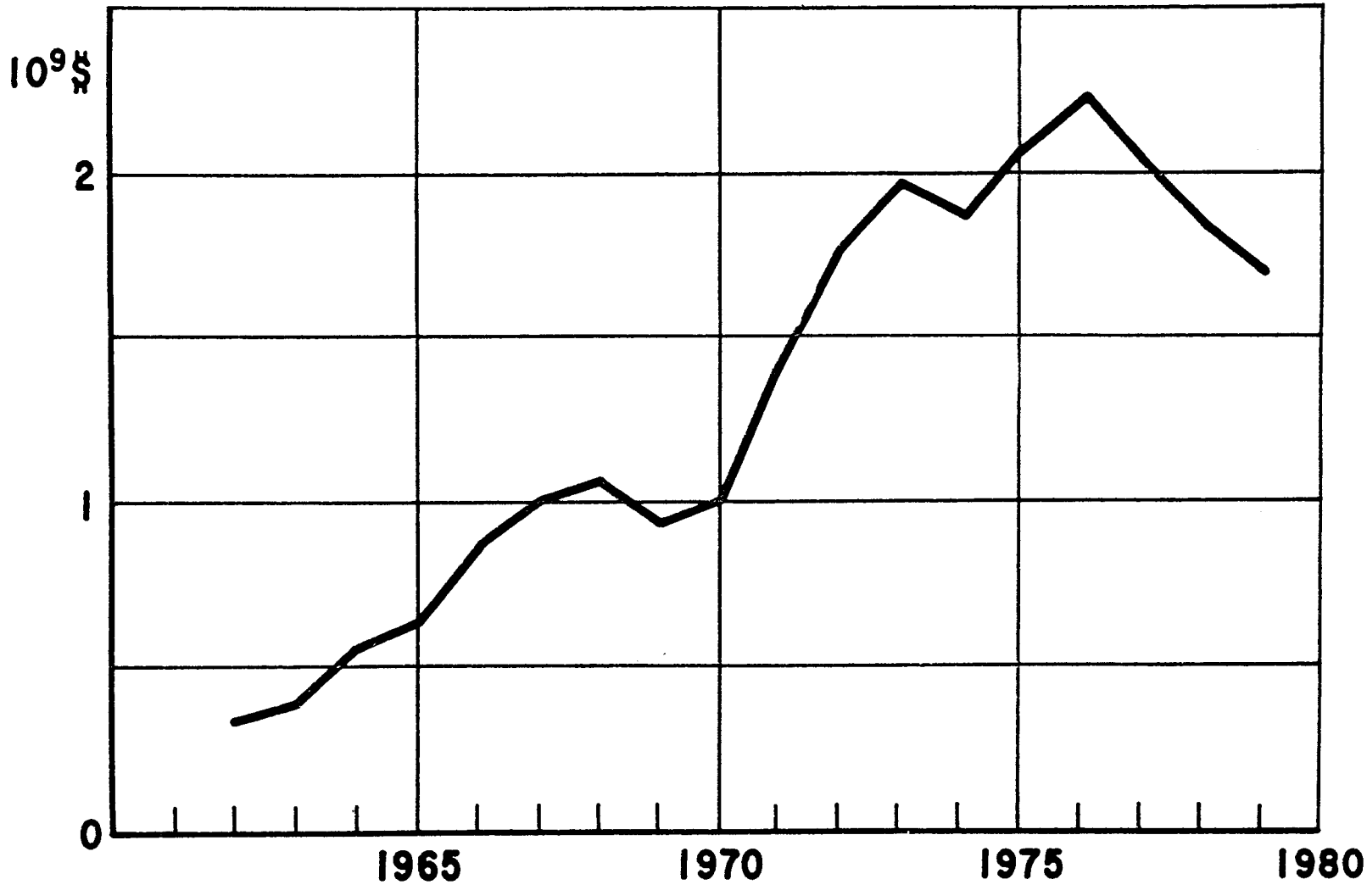

Figure 16

PROJECTED MISSION RELIABILITY

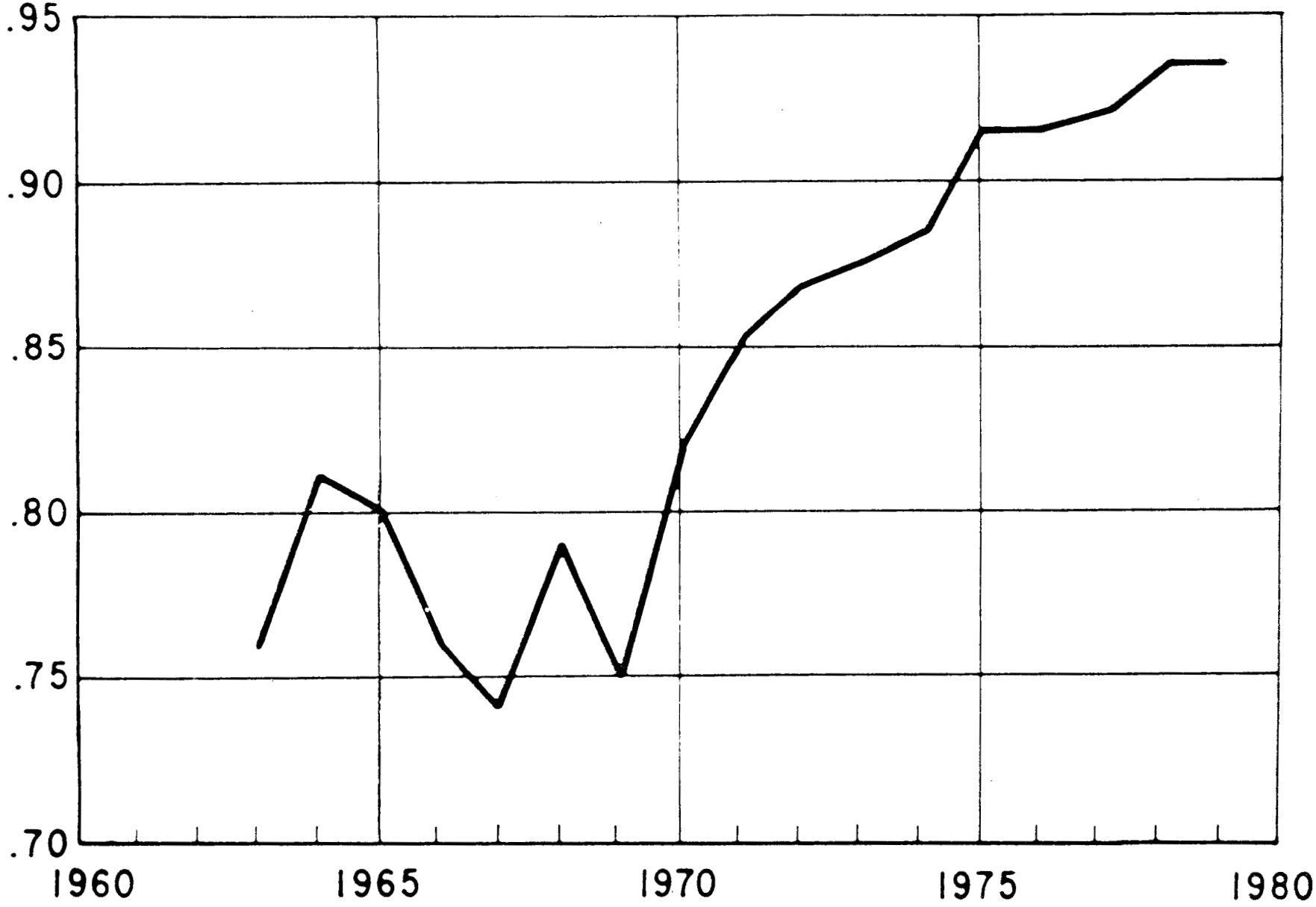

Figure 17

PROJECTED ANNUAL CARGO DELIVERY WEIGHT
(LOW ORBIT EQUIVALENT)

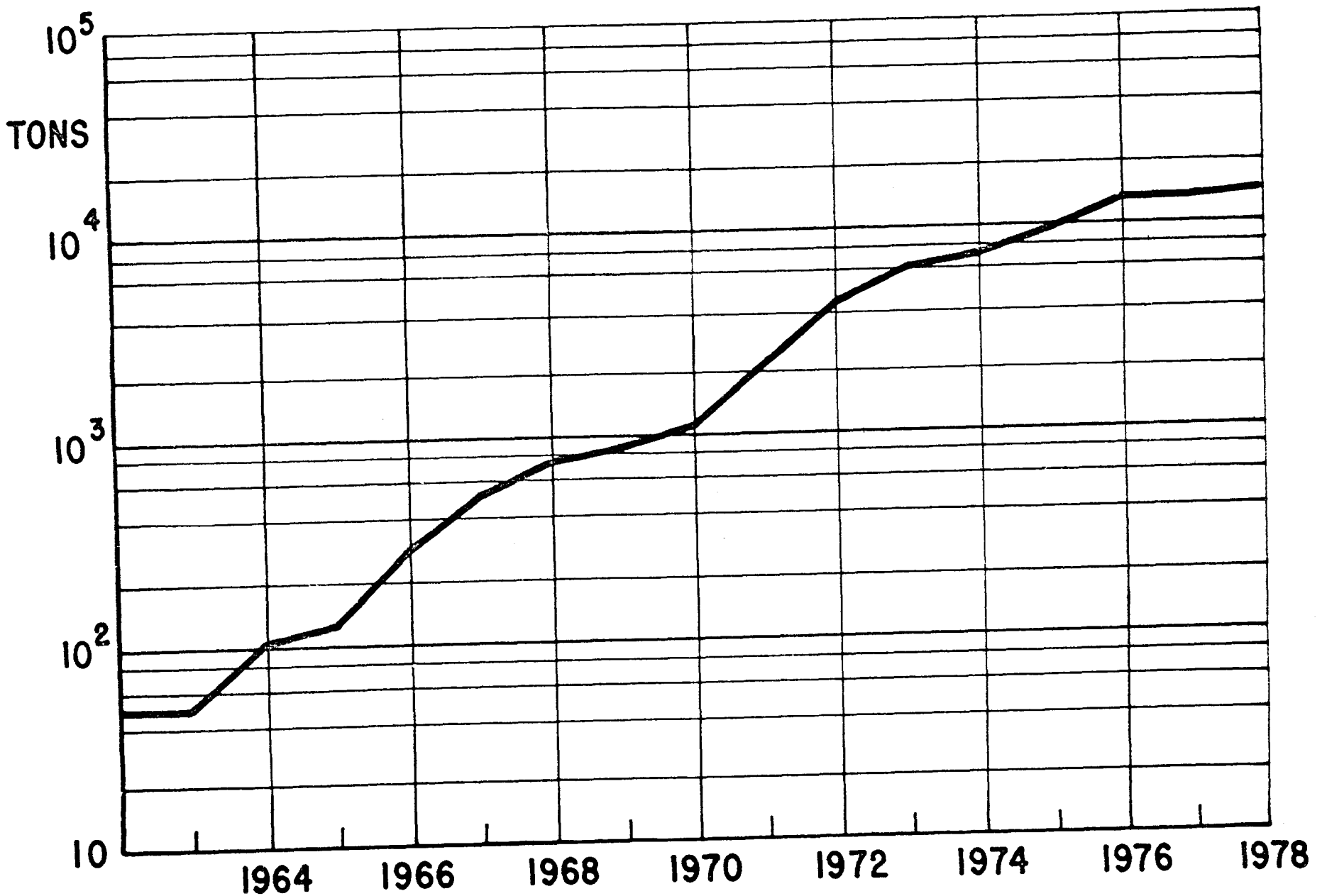

Figure 18

PROJECTED DIRECT OPERATING COST

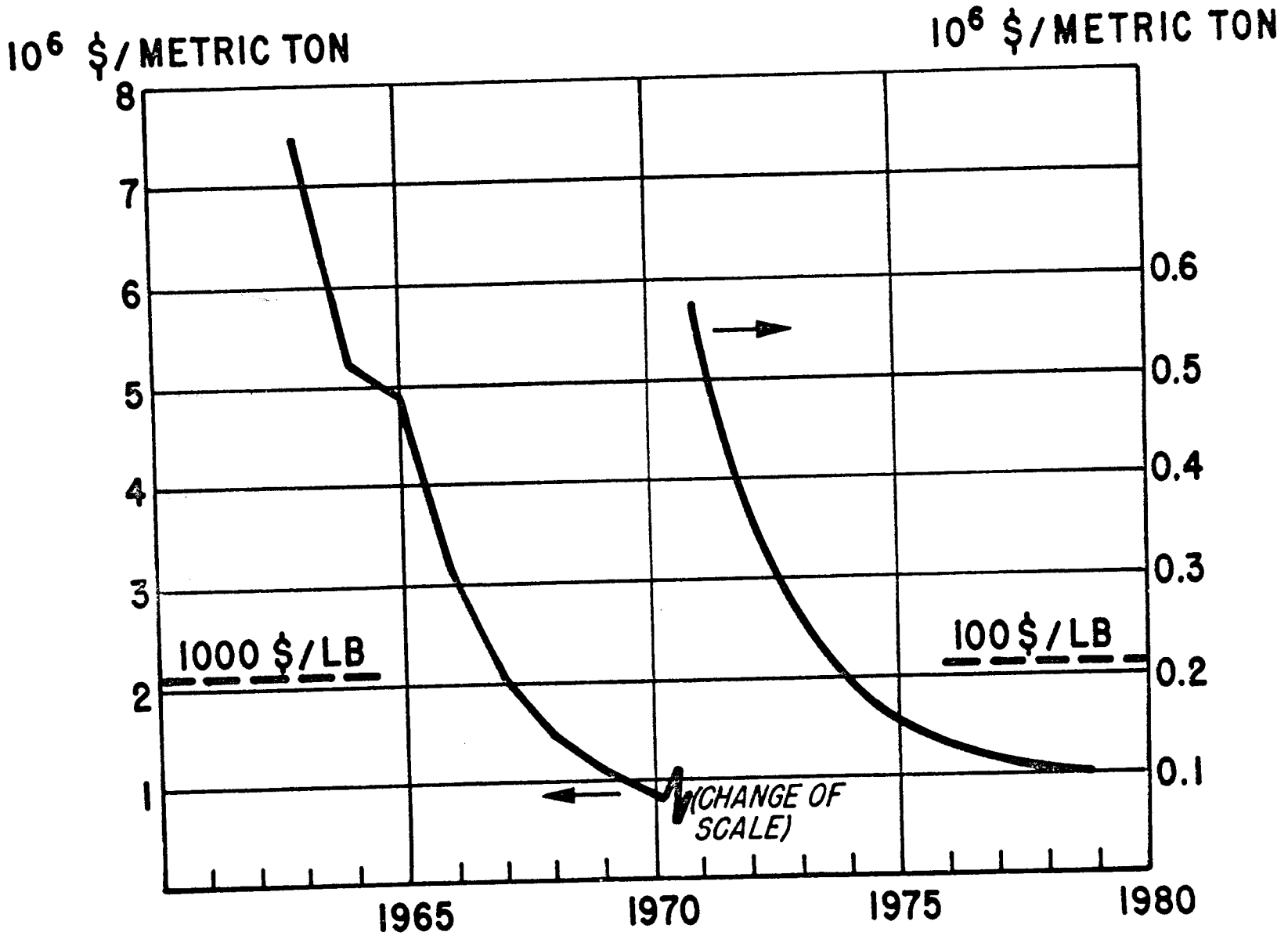

Figure 19

PROJECTED DIRECT OPERATING COST FOR PERSONNEL TO EARTH ORBIT

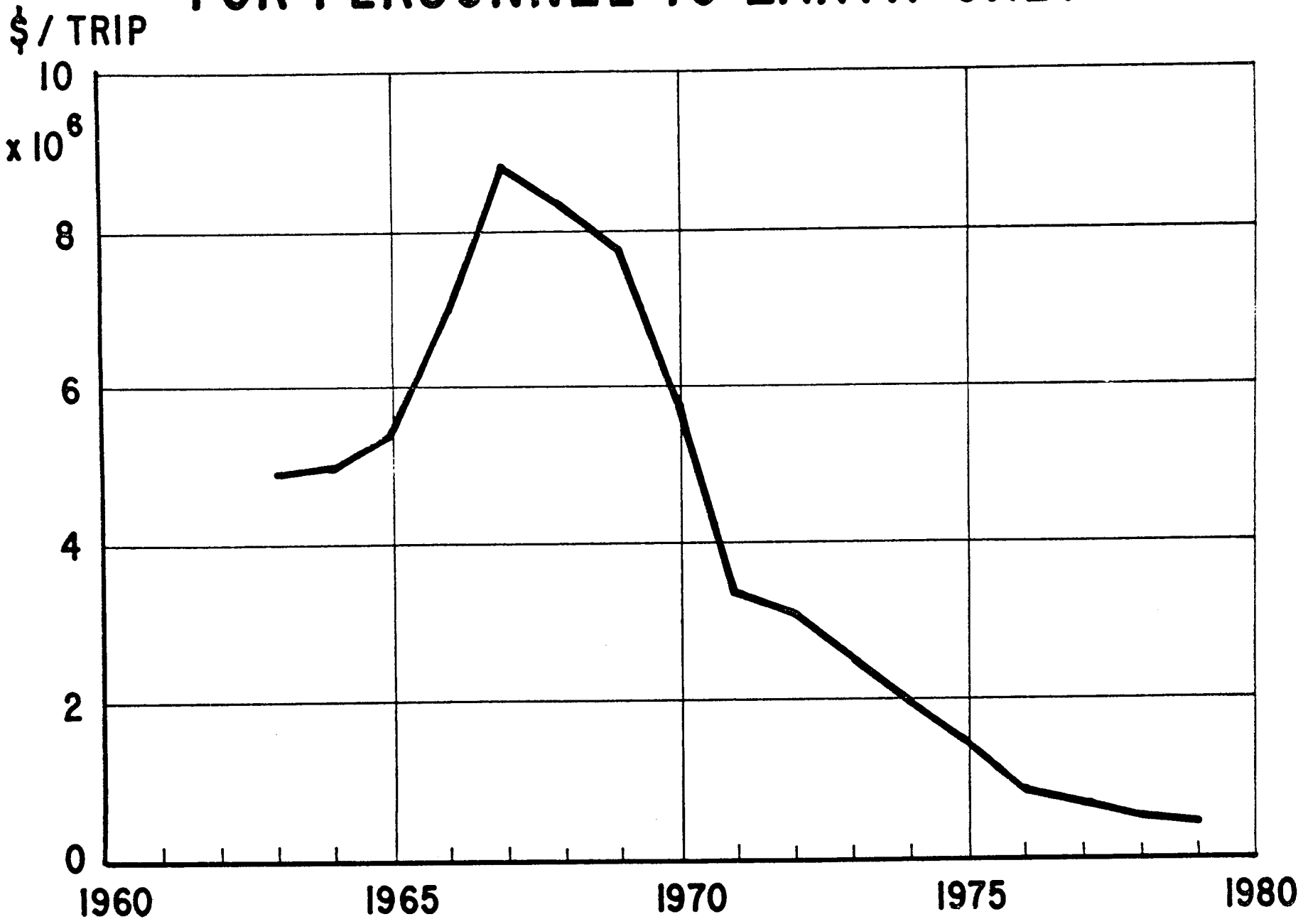

Figure 20

PROJECTED TREND $/ DAY IN EARTH ORBIT (DIRECT OPERATING COST)

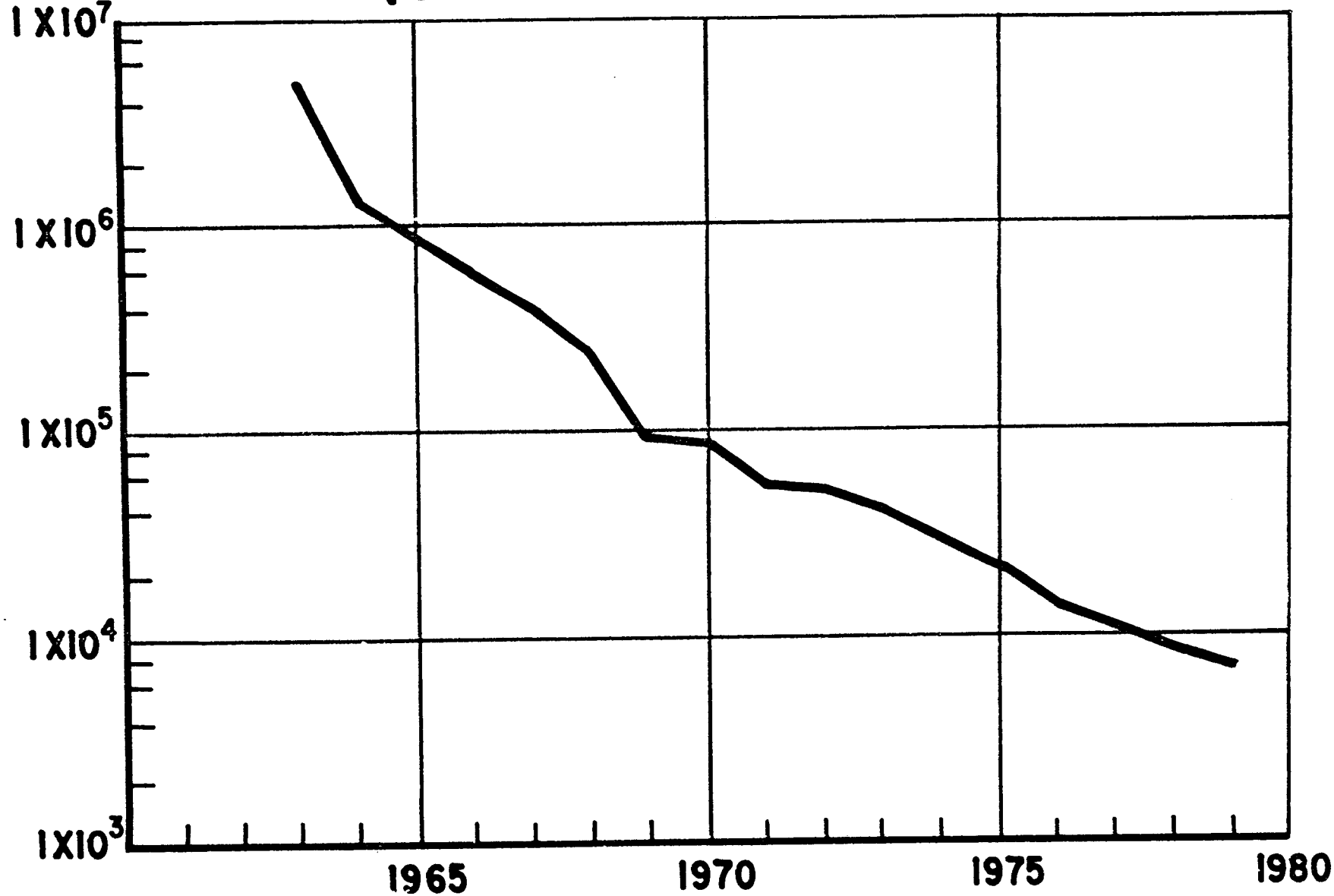

Figure 21

PROJECTED ANNUAL PASSENGER TRIPS TO EARTH ORBIT (HYPOTHETICAL MODEL)

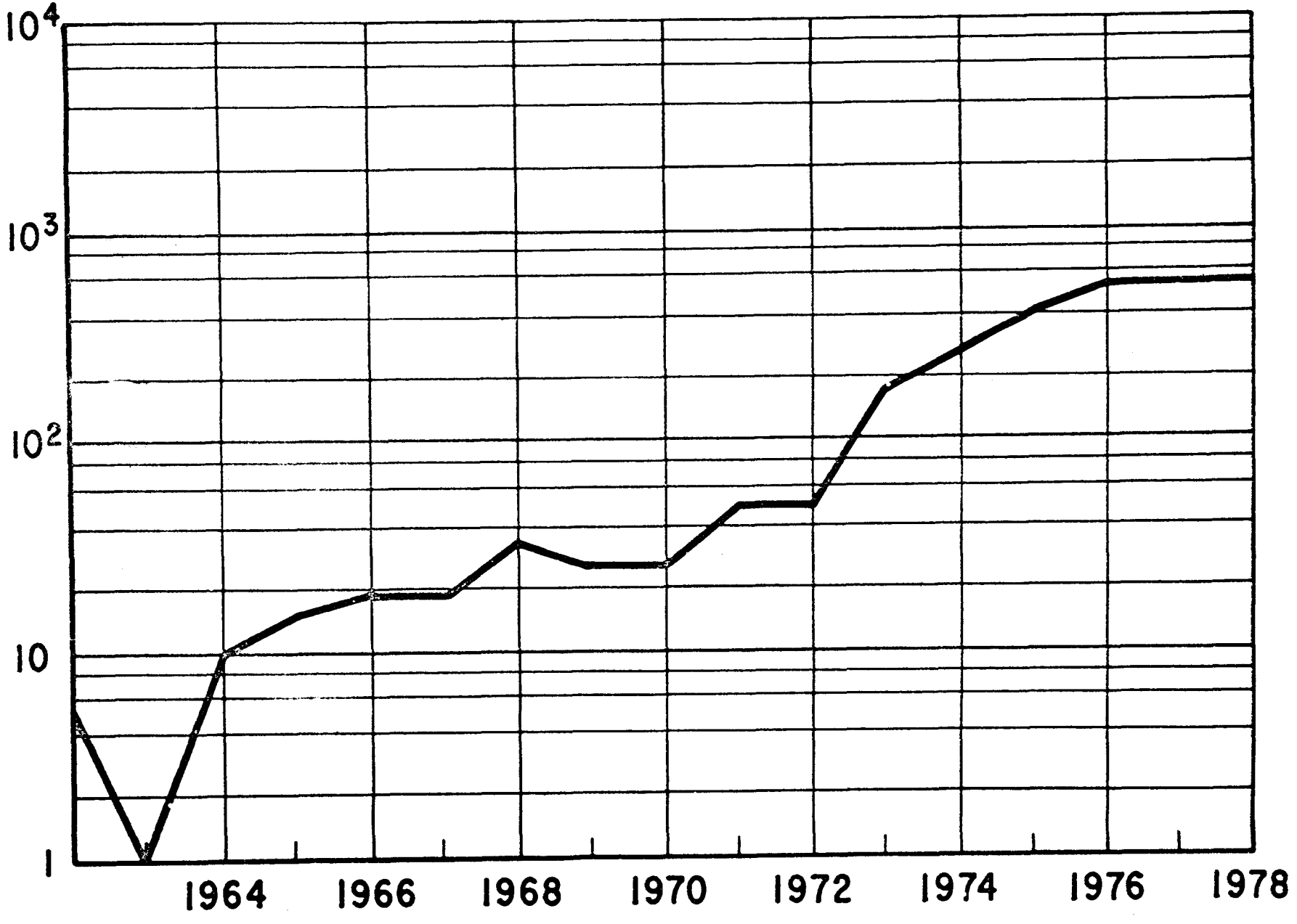

Figure 22

TRENDS OF SPECIFIC TRANSPORTATION COST TO EARTH-ORBIT (DOC) FOR CARGO

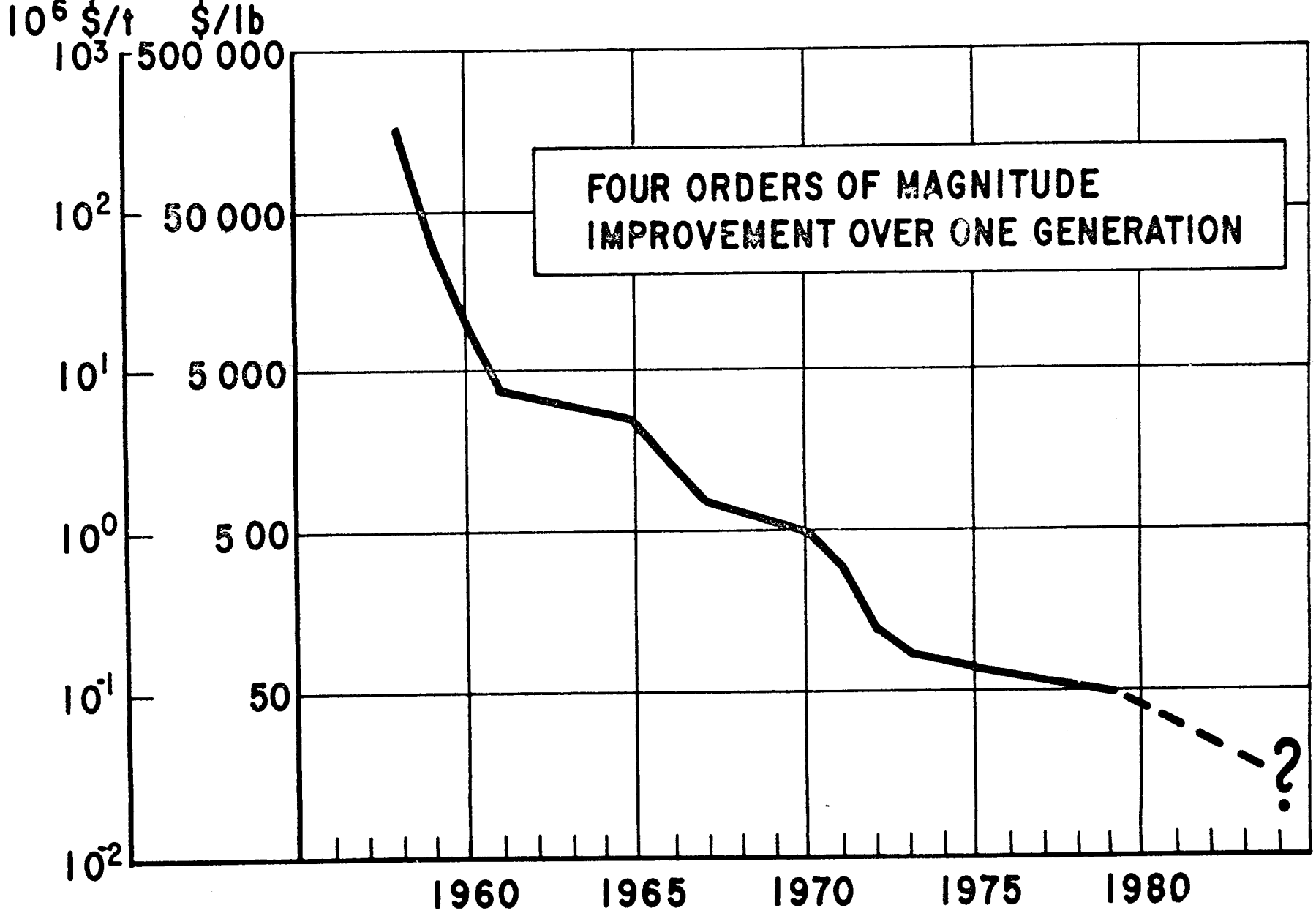

Figure 23

ORBITAL PAYLOAD DELIVERY RATE PROJECTED